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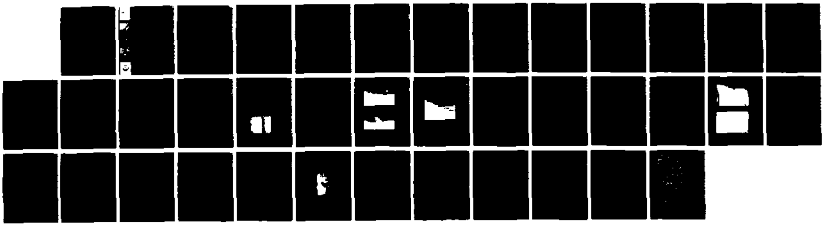

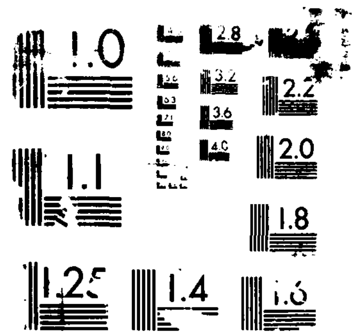
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MISCELLANEOUS PAPER CERC-87-21

FLOATING TIRE BREAKWATER TESTS PICKERING BEACH, DELAWARE

by

Peter J. Grace, James E. Clausner

Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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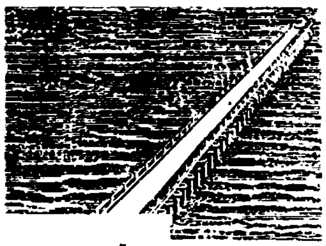
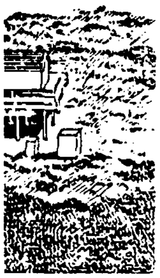
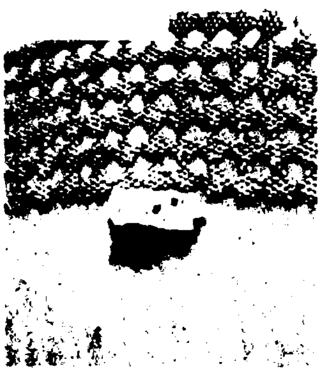
US Army Corps of Engineers







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This report documents a 1-week-long field monitoring effort conducted at Pickering Beach, Delaware. The purpose of the study was to gain information concerning mooring line response of a floating breakwater subjected to boat-generated waves. Data are compared with similar results of previous field studies.

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PREFACE

The study described herein was authorized by the Office, Chief of Engineers (OCE), US Army Corps of Engineers, and performed as part of Civil Works Research and Development Work Units 31232 (Evaluation of Navigation and Shore Protection Structures) and 31679 (Design of Floating Breakwaters). Funds were provided through the Coastal Structures Evaluation and Design Program. The work was performed by the Coastal Structures and Evaluation Branch (WESCD-S), the Wave Research Branch (WESCW-R), and the Prototype Measurement and Analysis Branch (WESCD-P) of the Coastal Engineering Research Center (CERC) at the US Army Engineer Waterways Experiment Station (WES). The study was coordinated and performed in cooperation with the US Army Engineer District, Philadelphia (NAP), and the Delaware Department of Natural Resources and Environmental Control (DDNREC). Messrs. John H. Lockhart, Jr., and John G. Housley were OCE Technical Monitors.

The work was conducted under the general supervision of Mr. D. Donald Davidson, Chief, Wave Research Branch; Ms. Joan Pope, Chief, Coastal Structures and Evaluation Branch; Mr. C.E. Chatham, Chief, Wave Dynamics Division; Mr. Thomas W. Richardson, Chief, Engineering Development Division; Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC; and Dr. James R. Houston, Chief, CERC.

The authors gratefully acknowledge the assistance of Messrs. Robert Henry (DDNREC), John Bartholomeo and Jeffery A. Gebert (NAP), C. Ray Townsend (WESCD-P), and Ms. Pope (WESCD-S) for their involvement throughout the planning, execution, and documentation of the test program; Messrs. Ted Keon (NAP) and Perry Reed (WESCD-S) for their help in photographing the tests and preparing the site for monitoring; and Mr. William Hegge (WESCD-P) for his assistance with the data analysis.

COL Dwayne G. Lee, CE, was Commander and Director of WES during the preparation and publication of this report. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimetres
kips (1,000 pounds, force)	4.448222	kilonewtons
knots	1.8504	kilometres per hour
miles (US statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

FLOATING TIRE BREAKWATER TESTS

PICKERING BEACH, DELAWARE

PART I: INTRODUCTION

1. Past experiences have demonstrated that floating breakwaters can be effective in the reduction of wave heights. Different types of floating breakwaters include floating tire breakwaters (FTB's), pole tire, timber caisson, steel caisson, log boom, and concrete ladder floating breakwaters. The FTB's have been used to reduce wave energy at over 50 low wave energy sites in the United States (Baird and Ross 1982). Most of these FTB's were built to protect small harbors and marina facilities. While a large number of model studies on wave transmission characteristics have been carried out, there have been few field tests documenting the performance characteristics (i.e., wave attenuation and mooring forces) of large scale FTB's. Prototype testing of a pipe tire FTB at Puget Sound, Washington, indicated that mooring line forces were substantially lower than expected (Nelson and Broderick 1986). Therefore, in an effort to increase knowledge of the FTB's performance, field tests were conducted on the breakwater at Pickering Beach, Delaware. Specifically, the primary purpose of the testing program was to determine the mooring forces on a shallow water FTB exposed to ship-generated waves. In addition, the amount of wave height reduction was investigated along with physical characteristics of the breakwater which could affect performance.

2. Under the Shoreline Erosion Control Demonstration Program (SECDP) (Office, Chief of Engineers 1981), two FTB's of different designs were installed at Pickering Beach, Delaware, in 1978. Later that year, winter storms combined with ice buildup severely damaged one breakwater section and displaced both breakwaters toward shore. The anchoring system was then improved and the remaining breakwater sections, which used a Goodyear Tire and Rubber Company design (Candle 1973), functioned until 1983. Between 1983 and 1984, mooring line failures allowed the Goodyear FTB to function only intermittently. The new Goodyear FTB installed at Pickering Beach in the latter half of 1984 was subjected to the tests described in this report.

3. In August of 1985, the Coastal Engineering Research Center (CERC) executed the FTB prototype tests at Pickering Beach. The tests were a joint

effort involving CERC, the US Army Corps of Engineers District, Philadelphia (NAP), and the State of Delaware Department of Natural Resources and Environmental Control (DDNREC). In addition to CERC research interests, the tests were conducted to provide NAP and DDNREC with information which could be used to improve the performance and durability of the Pickering Beach FTB. The tests consisted of measuring incident and transmitted wave heights and mooring line forces resulting from boat-generated waves.

PART II: BACKGROUND

Shoreline Erosion Control Demonstration Program

4. As a response to the findings of the National Shoreline Study (Department of the Army, Corps of Engineers 1971), the SECDP was authorized in 1974, as Section 54 of the Water Resources Development Act (Public Law 93-251). The National Shoreline Study determined that a significant portion of the nation's shoreline is privately owned (except in the State of Alaska) and is eroding. After recognizing the problem and being aware of the recreational and economic value of the shoreline, the US Congress created the SECDP. With this program, Congress authorized the Secretary of the Army to act through the Chief of Engineers in implementing a program to develop and demonstrate low cost methods for controlling or reducing shoreline erosion.

5. The purpose of the program was to give local and state governments, communities, and private individuals information on various low cost methods to help solve their shoreline erosion problems. The primary emphasis was on low energy coastline applications, since shoreline protection on open ocean coasts can seldom be considered a low cost undertaking.

6. Two project sites were chosen on each of the Atlantic, Pacific, Gulf, and Great Lakes Coasts. Six other test project sites, one of which is Pickering Beach, Delaware, were assigned to the Delaware Bay area. This report concerns itself solely with the Pickering Beach FTB project.

Site Description

7. Pickering Beach, Delaware, is a small summer resort with a 0.4-mile-long* section of beach on the western shore of Delaware Bay. It is located approximately 34 miles from the mouth of the bay and 10 miles east of Dover, Delaware (Figure 1). Sand from inshore sources was used to supplement the existing pocket beach in 1962 and 1969, since little or no sand exists naturally in the littoral system. The width of the constructed beach above the high tide line is approximately 40 ft with a 1 to 10 slope. Offshore, the slope decreases to approximately 1 to 20 for about 100 ft, then flattens to

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* A table of factors for converting non-SI units of measurements to SI (metric) units is presented on page 3.

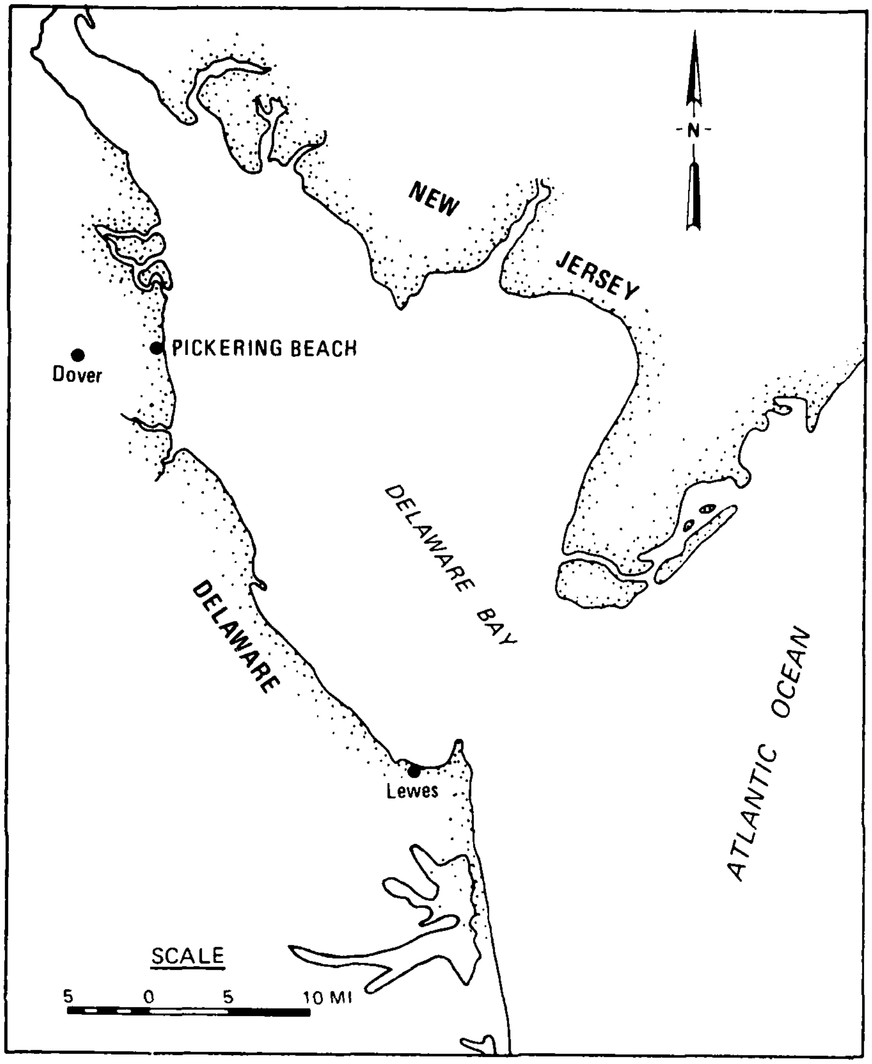

Figure 1. Location map of Pickering Beach, Delaware

the natural bay slope on the order of 1 to 800. In 1978, Pickering Beach was renourished to its original dimensions. The majority of the sand was placed before the FTB's were installed. A small amount of sand was added in 1979 along the southern end of the beach where the FTB is located.

8. The climate and tides experienced at Pickering Beach result primarily from its proximity to the Atlantic Ocean. Most waves reaching the shoreline of Delaware Bay are generated by local winds, and, consequently, have relatively short periods (1 to 5 sec). Wave heights are correspondingly small, seldom exceeding 6 ft due to limited fetch lengths and water depths. Average wave heights are usually 1 to 2 ft or less with typical storms

occasionally generating 4- to 5-ft waves with 4- to 5-sec periods. Waves at Pickering Beach usually approach the shoreline from east-northeast. Tides are semi-diurnal with a mean range of 5.2 ft and a spring range of 6.3 ft.

Project History

9. Under the SECDP, two different FTB designs were placed at Pickering Beach in an effort to protect the recreational beach. The breakwater designs tested were a modified Wave-Maze design (Noble 1969) and the Goodyear design. Two sections of each breakwater were to be tested including a 20-ft-wide by 202-ft-long section and a 40-ft-wide by 202-ft-long section. The sections were anchored approximately 1,000 ft offshore. Water depths at the site ranged from 5 to 6 ft at mean low water (MLW).

10. The Wave-Maze breakwater uses a five tire module as its basic building unit, and connections are accomplished with nuts, bolts, and washers (Figure 2). The wider section (40 × 202 ft) was designed to encompass 945 modules (15 wide × 63 long) while the narrower section (20 × 202 ft)

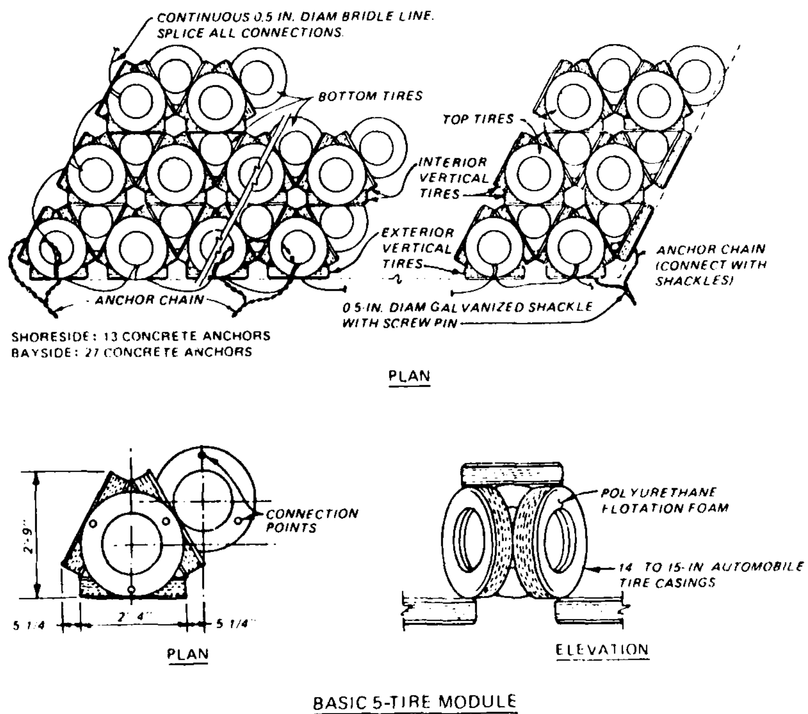

Figure 2. Wave-Maze design breakwater used at Pickering Beach (Office, Chief of Engineers 1981)

contained 441 modules (7 wide × 63 long).

11. An 18-tire module serves as the basic unit of the Goodyear breakwater (Figure 3). The units are held together by two lengths of conveyor

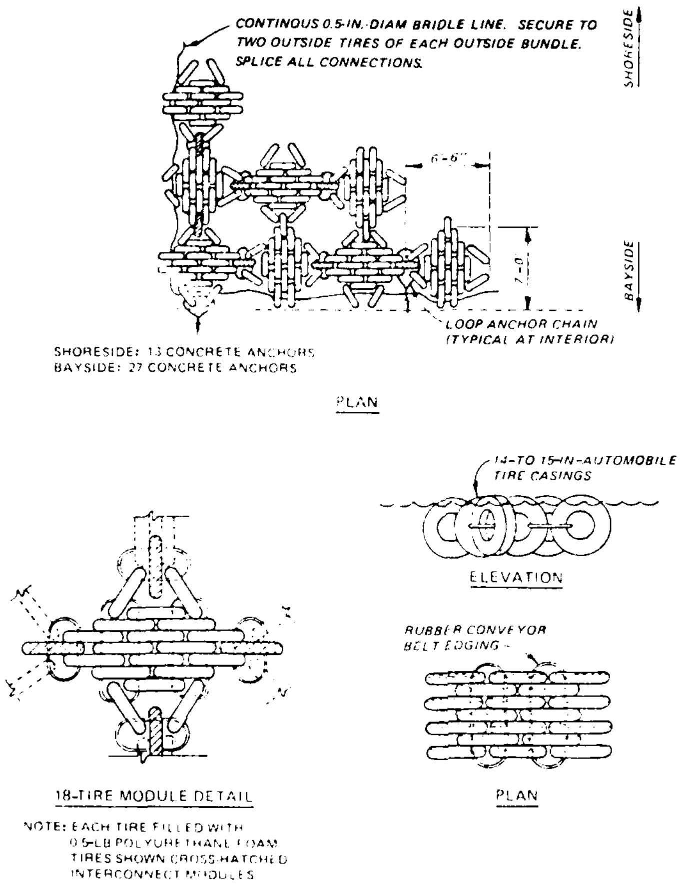

Figure 3. Goodyear design breakwater used at Pickering Beach (Office, Chief of Engineers 1981)

belting. The wider section contained 180 modules (6 wide × 30 long). A total of 90 modules (3 wide × 30 long) were used to construct the narrower section.

12. Each breakwater was initially anchored by eleven 4-ton concrete blocks with seven blocks on the bayside and four blocks on the landside. Offshore anchors were placed 56 ft from the structure and shoreward anchors were 52 ft from the structure. Each mooring line consisted of a 69-ft-long piece of 1/2-in.-diam galvanized chain.

13. Polyurethane foam placed in the crown of the tires provided buoyancy for the structures. The two foam components were mixed in liquid form before placement into the tires where they immediately underwent expansion at

a 3:1 ratio. One-half pound of foam was placed in the crown of all Goodyear breakwater tires. One pound of foam was placed only in the vertical tires of the Wave-Maze breakwater.

14. Construction of each breakwater was similar. The FTB's were constructed at the site in 50-ft-long sections, then towed into place and connected to adjacent sections.

15. Breakwater construction began late in the summer of 1978 and continued until December 1978, when inclement weather halted construction. At that time, both sections of the Goodyear breakwater and the narrower section of the Wave-Maze breakwater were complete, while 25 percent of the wider Wave-Maze section was in place. During the winter, large ice accumulations, estimated to be 1 to 2 ft thick, affected the area along with storm waves estimated at 3 to 4 ft high. These conditions resulted in substantial stress on the breakwaters, and, subsequently, caused damage. All four sections of the breakwaters were displaced 50 to 100 ft shoreward as the anchor blocks were dragged along the bottom and overturned. Apparently, wave and ice forces acted through the FTB's and mooring lines to displace individual anchor blocks along the muddy bottom.

16. The Goodyear sections generally remained intact and experienced only minor structural damage attributed primarily to failure of the conveyor belt material. Failed belts were located within the connections of the first two rows of modules on the seaward side, which is the area that absorbs the majority of wave stresses. The Goodyear breakwater is a more flexible structure than the Wave-Maze design, and was apparently able to withstand more ice and wave-induced stresses without damage.

17. Conversely, the Wave-Maze FTB experienced considerably more damage. Structural failure was attributed to forces caused by ice accumulation and amplified by storm waves. The more rigid structure of the Wave-Maze modules brought about stresses on bolted connections of magnitudes such that galvanized steel washers were deformed and pulled through the tire walls.

18. Damage caused by the winter storms forced the development of a new project plan. The damaged Wave-Maze breakwaters were eliminated from the program due to high repair costs. Anchor blocks for the Goodyear breakwater were replaced by 30-ft-long timber piles which were embedded 20 to 25 ft below MLW. The portions of the piles above +2 ft MLW were cut off to prevent ice jacking. In addition to these changes, the Goodyear structure was moved

300 ft closer to shore in order to increase its effectiveness. The water depth at this new location was 2 to 3 ft at MLW.

19. In 1980, the points at which the mooring lines attached to the breakwater were modified. In an effort to more evenly distribute the mooring forces along the length of the structure instead of loading a limited number of tires, 30-ft-long sections of 8-in.-diam timber piles were placed horizontally through the front row of modules. The anchor chains were connected to these horizontal piles at 15-ft spacings. The ends of adjacent horizontal piles were chained together to eliminate unnecessary longitudinal movement of the piles. In addition to these mooring alterations, the connections between the first and second rows of modules were reinforced with additional strapping.

20. After 1980, DDNREC took over responsibility for the Pickering Beach FTB. Since that time, mooring chain failures have been the major problem. Mooring chains on the 40-ft-wide section failed on 2 February 1983, and the structure came ashore on the north end of Pickering Beach. On 28 March 1984, mooring chains on the 20-ft-wide section failed, and the breakwater broke apart. Some modules were found as far away as Cape Henlopen, at the mouth of Delaware Bay.

21. The DDNREC decided to reinstall the 40-ft section in the summer of 1983, and construction started in 1984. Most of the original tires were used, but the rest of the structure consisted of new material assembled using improved construction techniques. The beads of the tires were pried apart prior to the use of the foam, then released after the foam had hardened to hold the foam in place more tightly. One-in.-diam holes were punched in the bottom of the tires to reduce sediment accumulation in the tire wells. The 1/2-in. galvanized anchor chain used on the original design had shown considerable wear in the 6-ft section adjacent to the structure prior to failure. In the newer FTB design, all anchor chains were replaced with 3/4-in.-diam synthetic braided ropes with a working load of 2,134 lb and an average breaking strength of 19,400 lb. Installation was completed during January 1985.

22. CERC, NAP, and DDNREC undertook subsequent testing of the new Pickering Beach FTB in August 1985 to follow up on the initial work and knowledge gained under the SECDP. The primary motive for the tests was to determine the performance characteristics of the Pickering Beach FTB when subjected to boat-generated waves.

23. Preliminary analysis of results obtained during a more extensive floating breakwater prototype study (Nelson and Broderick 1986) indicated that measured FTB mooring line forces were much less than the predicted loads. A 110-ft-long marine tug capable of generating a maximum wave height of 2.8 ft was used as the wake generating vessel. The maximum anchor line force measured in a line was 950 lb. This was in response to a wave height of approximately 2.2 ft and was recorded on a load cell near the connection of the anchor line to the breakwater. Although the measured loads were smaller than predicted loads, some wake generated mooring forces were of magnitudes similar to those forces caused by storm generated waves.

24. Therefore it was assumed that a series of boat wake tests performed at Pickering Beach would provide information relative to the typical mooring forces experienced at that site. These simpler tests at Pickering Beach were an opportunity to provide additional data concerning FTB performance in addition to furnishing information which might be used to improve the performance and durability of the structure.

PART III: EQUIPMENT

25. Due to the limited time and available funding allocated to this project, efforts were made to simplify the procedures when possible in order to minimize the chances of encountering difficulties and delays. In compliance with this decision, electronic monitoring equipment was limited to one wave gage and two anchor force load cells. A simple level-rod-type staff, graduated in 0.1-ft units was installed on the shoreward side of the breakwater to allow visual readings of the transmitted wave heights. CERC modified a conventional laboratory wave staff gage design to create the incident wave staff gage. This gage consisted of a length of PVC pipe around which a resistance wire was spirally wound (Figure 4). When installed and subjected

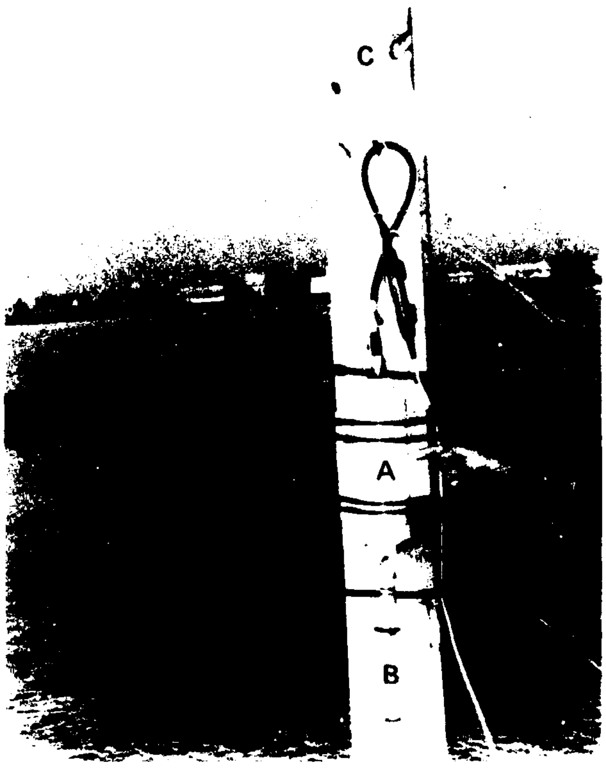

Figure 4. Electrical resistance-type incident wave gage (A = electronics, B = resistance wires, C = support)

to changes in water surface elevation, the gage measured electrical resistance which was proportional to the immersed length of the pipe. Mooring forces were measured with two 10-kip load cells previously used in the Puget Sound floating breakwater study mentioned above. Based on the results of this previous study, mooring loads at the Pickering Beach FTB were expected to be no greater than 1 kip per mooring line; therefore, the ultimate force measuring capability of the two load cells was significantly greater than that required for this particular study. However, a laboratory calibration of the cells indicated that they would effectively measure loads as low as 100 to 200 lb.

26. Time-histories of the boat wake heights and mooring loads were collected on a six channel Western Graph Tech electronic strip chart recorder located onboard a 19-ft MonArk boat moored directly behind the breakwater. The recorder was powered by a gasoline fueled generator which was also located onboard. In addition to serving as the control point for the data acquisition system (DAS), the MonArk was a convenient base from which observers could record visual readings of the transmitted wave heights, observe breakwater motions in response to the waves, and photograph the test procedures. Aerial photographs of the boat wake tests were also obtained during the first day of actual data collection (Figure 5).

27. During testing, all boat wakes were generated by the "Delaware," a 1969 Breaux Bay Craft crew boat, owned by the State of Delaware (Figure 6). The "Delaware" is an aluminum hull vessel powered by two GM 871 diesel engines and twin screw propulsion. It is 46 ft long and has a 17-ft beam, 3-ft 8-in. draft, and a 20-ton displacement. Maximum obtainable speed was 26 knots.

28. Due to the relatively shallow water conditions at the site, duration of high tide allowed safe operation of the 3-ft, 8-in. draft "Delaware" for only about 2 hr each day. A schedule of test runs was prepared specifying boat speed, sailing line distances from the breakwater, and direction/angle of vessel approach. This information is listed along with test results in Table 1.

Figure 5. Aerial photographs of FTB testing

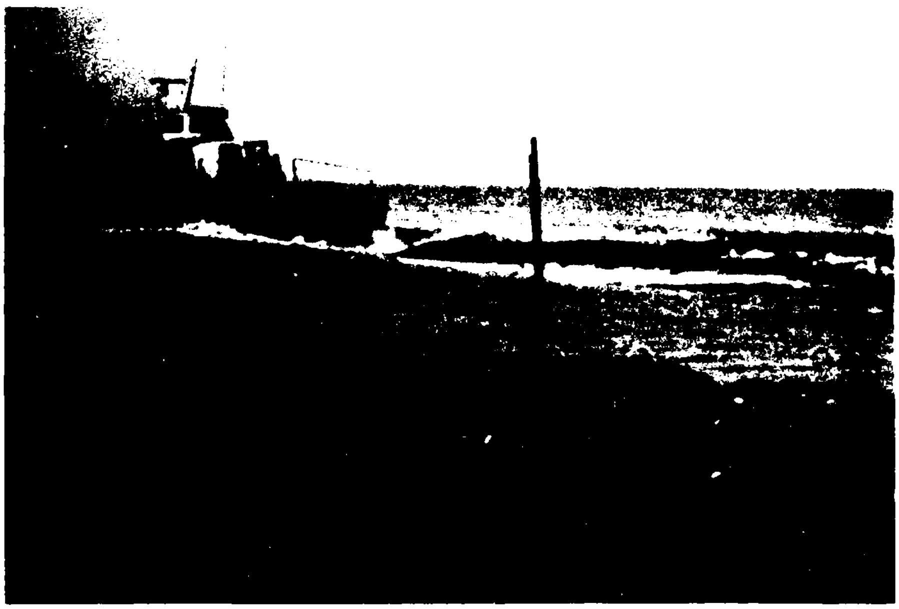

Figure 6. Boat wakes were generated by the "Delaware"

PART IV: PREPARATION AND PROCEDURE

29. Preparation of the test site and DAS was scheduled on the first day of the week-long effort. This involved (a) assembly of the incident wave gage, (b) preparation of waterproof connections, (c) installation of the two anchor line load cells, (d) placement of solid supports to secure the wave gages and all cables, and (e) positioning of buoys to mark sailing lines to be followed by the wake generating vessel. The original test plan called for installation of the two load cells on one of the northern corner anchor lines; however, the first visit to the site revealed that this line was broken and the adjacent anchor line was instrumented instead (Figure 7).

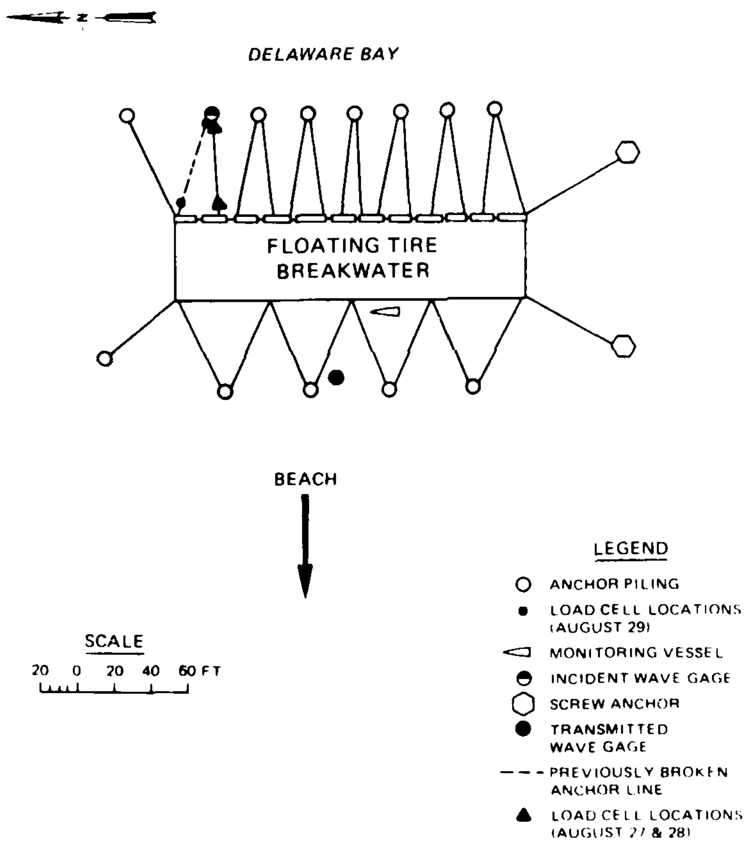

Figure 7. Project site

30. Initial attempts to collect data indicated that although the incident wave gage was functioning properly, the load cells detected no measurable anchor line forces. It is common practice for the floating breakwater design to provide sufficient slack in the mooring lines in order to maintain a proper

catenary depending on the type of anchor used, and to prevent breakwater submergence during high tides (Eckert, Giles, and Smith 1978). The maximum normal tidal range at Pickering Beach (6 to 8 ft including wind set up) warrants a considerable amount of slack in the moorings at this site. Due to this slack, westerly winds of 10 to 12 mph had pushed the breakwater to the east, thereby increasing the slack in the bayward lines as the shoreward lines became taut. Since the "Delaware" could pass safely only on the east side of the breakwater, the anchor line load cells were mounted on that same side. The amount of slack in the instrumented anchor line was such that breakwater motion in response to boat wakes was not sufficient to induce a measurable force in the line.

31. Similar weather and winds were predicted for the following day; therefore, measures were taken to remove the slack from the eastern mooring lines. Working conditions were most favorable at ebb tide, when water depths were only 1 to 2 ft and the breakwater was resting on the bay bottom (local siltation caused by the breakwater has reduced depths by an average of 1 ft). At that time, the slack from each of the bayward anchor lines was gathered and U-bolt type wire rope clips were installed to ensure that the lines would be taut at high tide.

32. Further attempts to collect boat wake data were begun the following morning. Winds were from west-southwest at approximately 12 mph and it appeared that, due to modifications made during low tide of the preceding day, the bayward lines would be sufficiently taut to ensure measurable loads on the instrumented anchor line. The first few test runs indicated that the wave gage and one of the load cells were functioning properly; however, the load cell mounted at the anchor piling was not responding. Nevertheless, testing was continued and successful data acquisition was accomplished from the wave gage and the single working load cell.

33. That afternoon, as the tide receded, the break in the previously mentioned anchor line on the breakwater's northeast corner was repaired. The functional load cell was then mounted on this line near the connection at the anchor piling. A defective seal was discovered in the watertight load-cell-to-cable connection. This connection was replaced.

34. The next morning testing began on schedule with all instruments functioning correctly. A total of 49 boat passes were recorded before the falling tide forced departure of the "Delaware."

PART V: TEST RESULTS

35. Successful data acquisition was accomplished on two occasions, encompassing a total of 87 boat passes. Data from 13 of these runs were useless because of signal noise or the temporary malfunction of the DAS. Transmitted wave heights were recorded for only 49 of the passes. In general, the time series data were all of similar appearance, characterized by a wake record with three or four predominant wave components and corresponding anchor line force records with one predominant peak (Figure 8). Due to these common characteristics, the wave records were digitized using the points illustrated in the typical record sketched in Figure 9. The incident wave height and

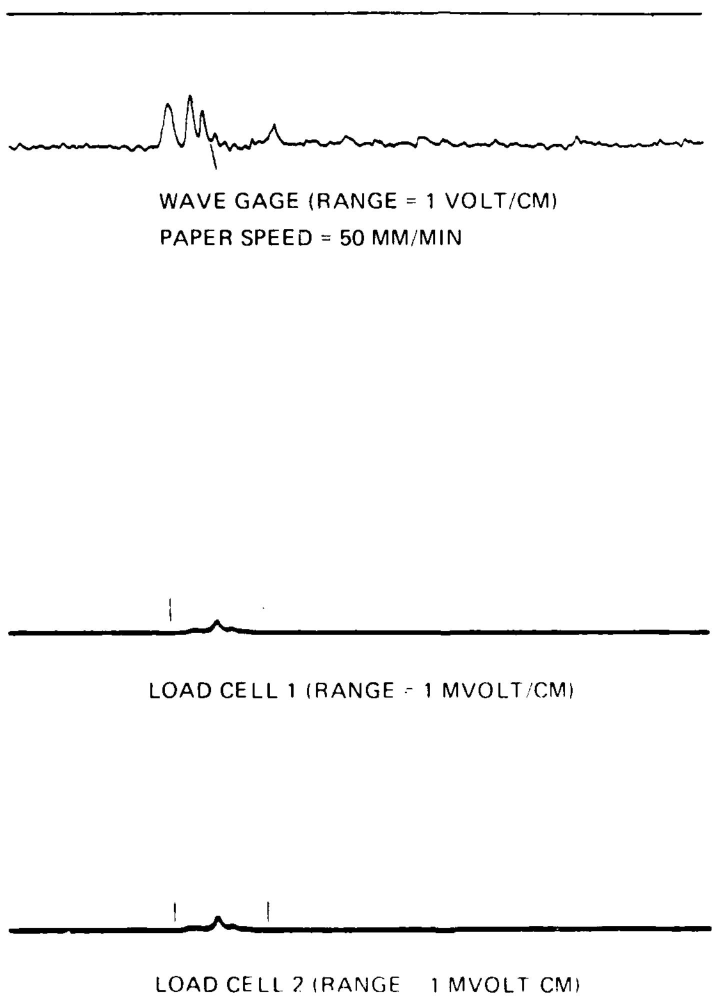

Figure 8. Typical time-history from strip-chart recorder

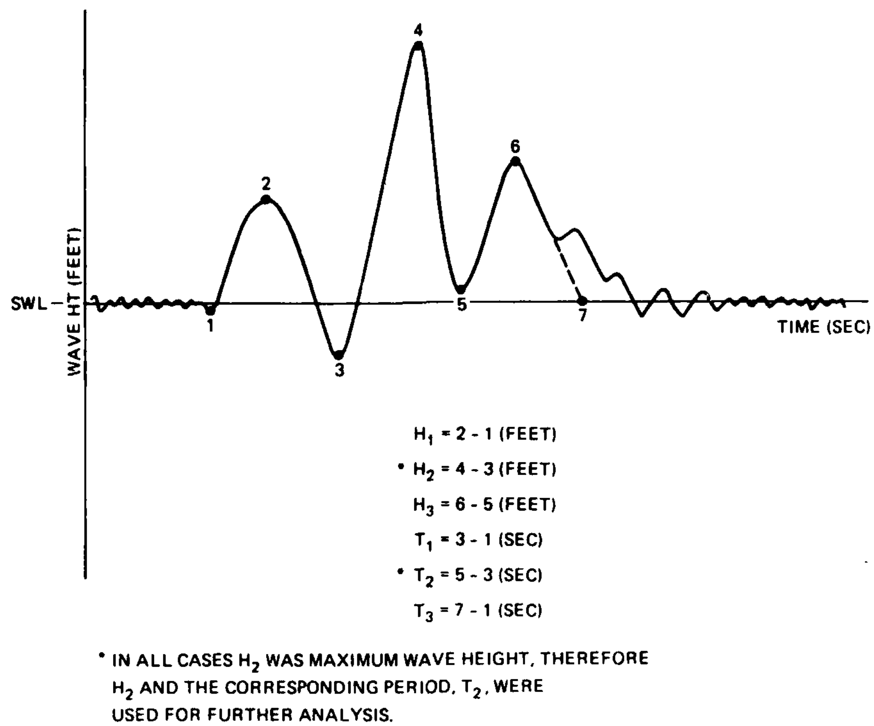

Figure 9. Sketch of typical wave record depicting points used for digitizing wave data

corresponding period were chosen as the largest wave, which was the second wave in each wake series. T3 is a description of the total time elapsed as the three largest waves passed the gage. Anchor line forces were recorded based on the magnitude of the single greatest peak. Transmitted wave heights were recorded by an observer who watched the wakes pass a graduated staff mounted behind the breakwater.

36. The results of all data collection efforts for each run are listed in Table 1. The 45-deg wave angle implies that the boat proceeded in a line parallel to the long axis of the breakwater. Due to the typical pattern of wave crests produced by a moving vessel, the breakwater was subjected to angular wave attack (Figure 10). In an attempt to generate a series of boat wakes with crests parallel to the breakwater's long axis, the 90-deg wave angle conditions were included (Figure 11). Ideally, parallel crests could have been generated by having the boat pass in a straight line at some angle to the FTB's long axis. Submerged pilings near the breakwater and shallow water made these types of runs impossible.

37. The "Delaware" was unable to generate high boat wakes. At a

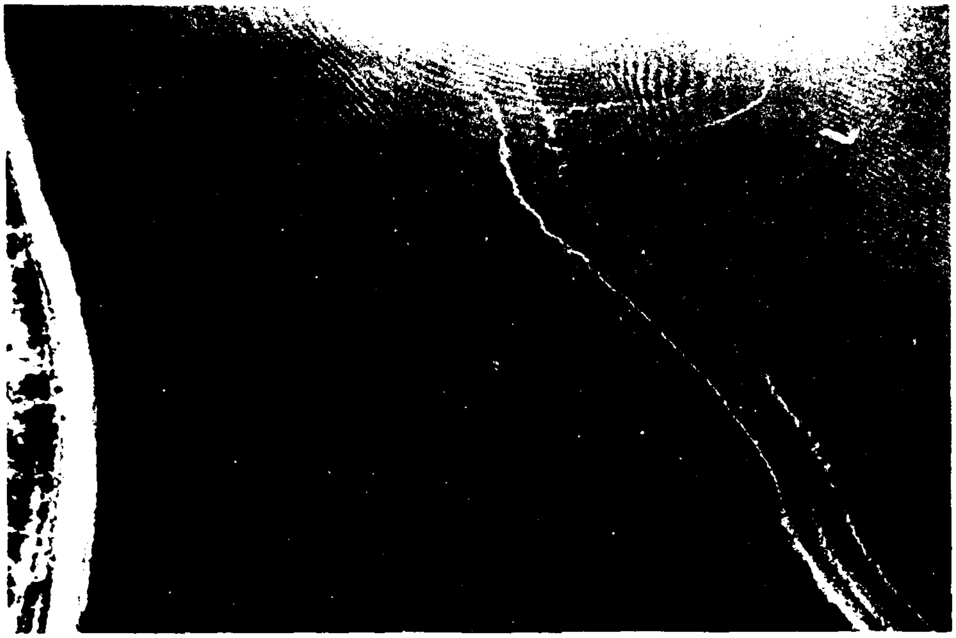

Figure 10. Angular waves approaching the breakwater

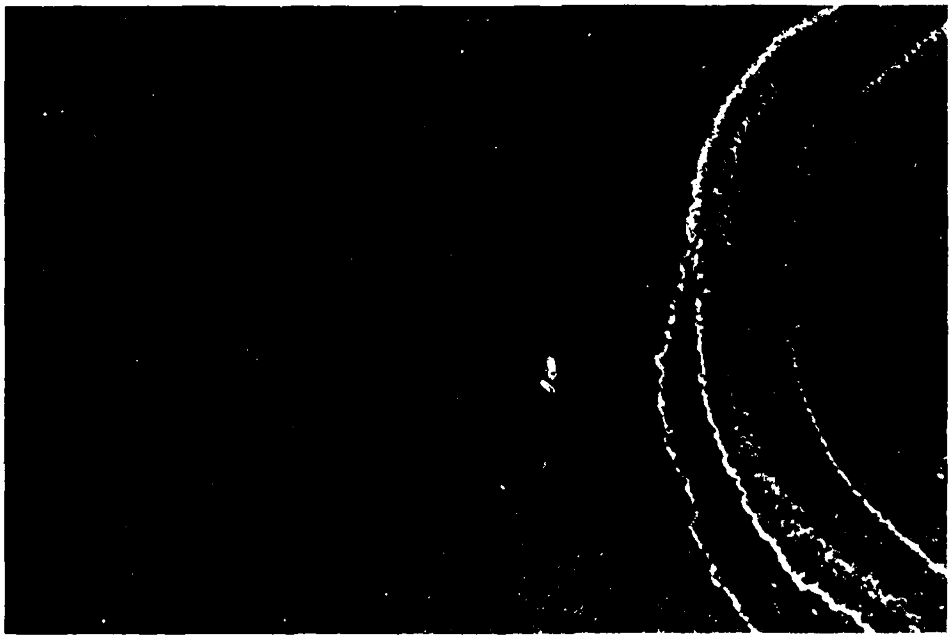

Figure 11. Attempts were made to produce waves with crests parallel to the long axis of the breakwater

maximum speed of 26 knots, an angular approach with the sailing line approximately 75 ft from the breakwater resulted in an incident wave height of 1.6 ft. As expected, there was generally a decrease in wave height as the boat speed was reduced. In most cases, the height of the wake also decreased as the distance from the sailing line to the breakwater increased. This reduction in wave height was significant, indicating that, in most cases, much wave energy was dissipated as the waves approached the breakwater from the more distant sailing lines. This was often observed as some of the boat wakes moved into shallower water, becoming noticeably steeper and spilling before reaching the breakwater. However, two of the largest wakes recorded (1.0 and 1.3 ft) were produced at a low boat speed (15 knots) with an angular sailing line located 200 ft from the breakwater; therefore, certain combinations of large vessels passing at slower speeds and greater distances from the breakwater could produce relatively large wave heights. Nevertheless, almost all of the highest boat-generated waves to which the FTB will be subjected will arise from smaller vessels passing near the breakwater at maximum speeds. This agrees with the findings of a study on characteristics of ship wakes in Oakland Estuary, California (Sorensen 1967). It should be noted that wind-generated waves can be larger and produce greater loads on an FTB.

38. The small wave heights which resulted from many of the test runs made visual recording of the transmitted wave heights quite difficult. If incident wave heights were less than 0.5 ft, no waves were detected at the transmitted wave staff. The limited amount of wave transmission data which were collected are presented in Figures 12 and 13, plots of transmission coefficient versus incident wave height and period, respectively. The transmission coefficient is the ratio of transmitted wave height to incident wave height and it is a measure of the energy dissipating performance of the breakwater. Figures 12 and 13 indicate that the transmission coefficient was 0.66 with a standard deviation of 0.08 for wave heights less than 1 ft. For incident wave heights greater than 1 ft, the data show dissipation of approximately 40 to 70 percent of the wave height. These results for the larger incident waves are similar to FTB wave transmission characteristics measured in previous testing. Thus, it is possible that the visual observation method of recording the transmitted wave heights did not yield results with sufficient accuracy, especially in the range of wave heights less than 0.5 ft.

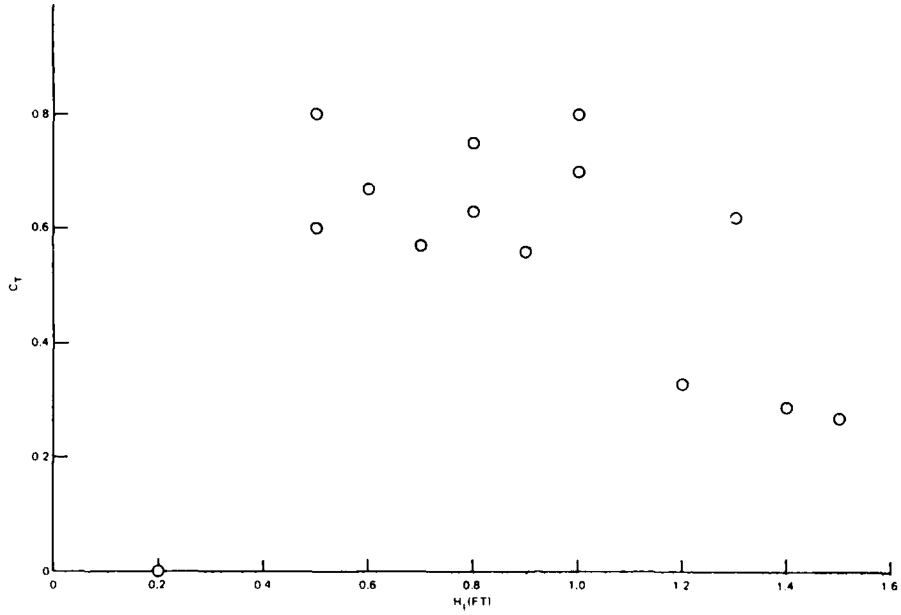

Figure 12. Transmission coefficient, C_T, versus incident wave height, H_i

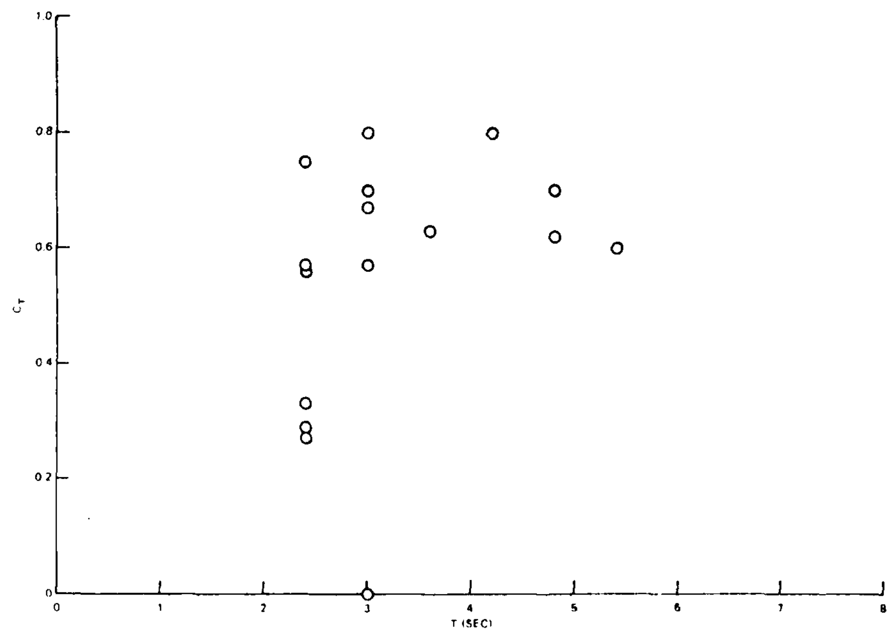

Figure 13. Transmission coefficient, C_T, versus incident wave period, T

39. The FTB's mooring line force response is presented in Figures 14 and 15. A maximum force of 281 lb was recorded in response to the 1.6-ft maximum wave height generated. An increase in mooring line force with increasing incident wave height is demonstrated in Figure 14, which presents the mooring force data collected at the connection to the breakwater relative to incident wave heights. In all cases the maximum incident wave height was that wake corresponding to H_2 of the digitizing process described in Figure 9. Although a linear trend is apparent, a linear regression yielded a relatively poor correlation of approximately 30 percent. For the purpose of this study, it is sufficient to note that although mooring line forces did increase with increasing incident wave heights, at no time did any of the boat-generated waves bring about a load greater than 281 lb in a mooring line. A plot of anchor loads versus incident wave period failed to suggest any relative trend, primarily because of the similarity in period of the wakes generated by the "Delaware." Almost all of the highest wakes were characterized by periods of 2.5 to 5.0 sec. The data also indicated that there was little difference between the force magnitudes recorded simultaneously in the two load cell locations (i.e., at the piling (P1),and at the breakwater(P2)). When there was a measurable difference in the loads, the greater force was measured in the cell near the connection to the breakwater (Figure 16). This is in agreement with results of the Puget Sound study, which indicated that forces measured at the breakwater were approximately 25 percent greater than the corresponding forces measured at the piling (Nelson and Broderick 1986). At this time an explanation for the occurrence of lesser loads at the piling is speculative. One factor which may have been involved is the dissipation of energy through friction and drag as the mooring line moved through the water in response to the waves.

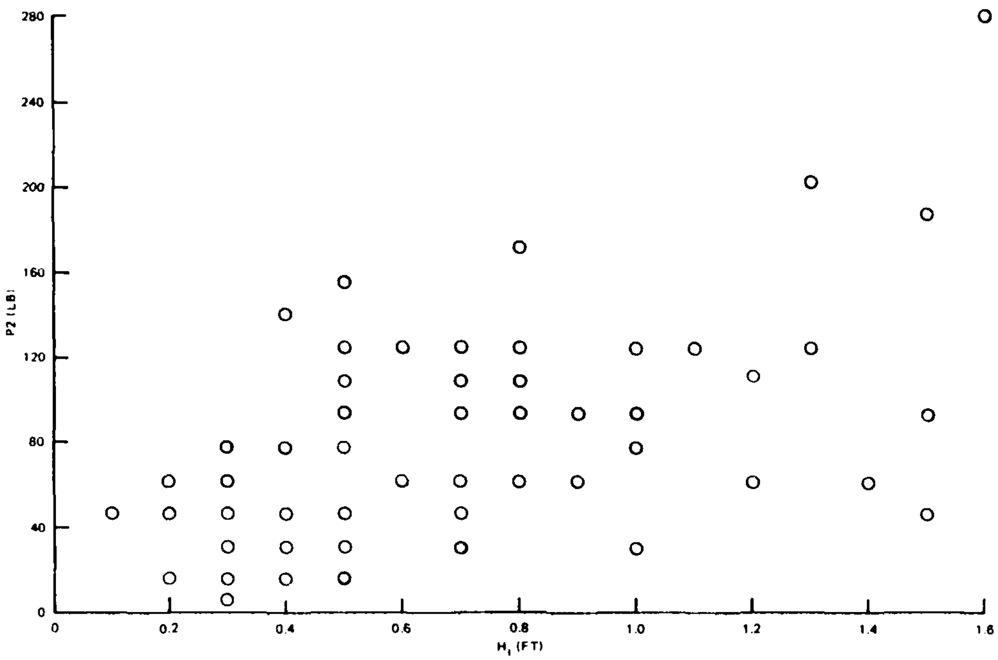

Figure 14. Anchor load at breakwater connection, P2, versus incident wave height, H_i

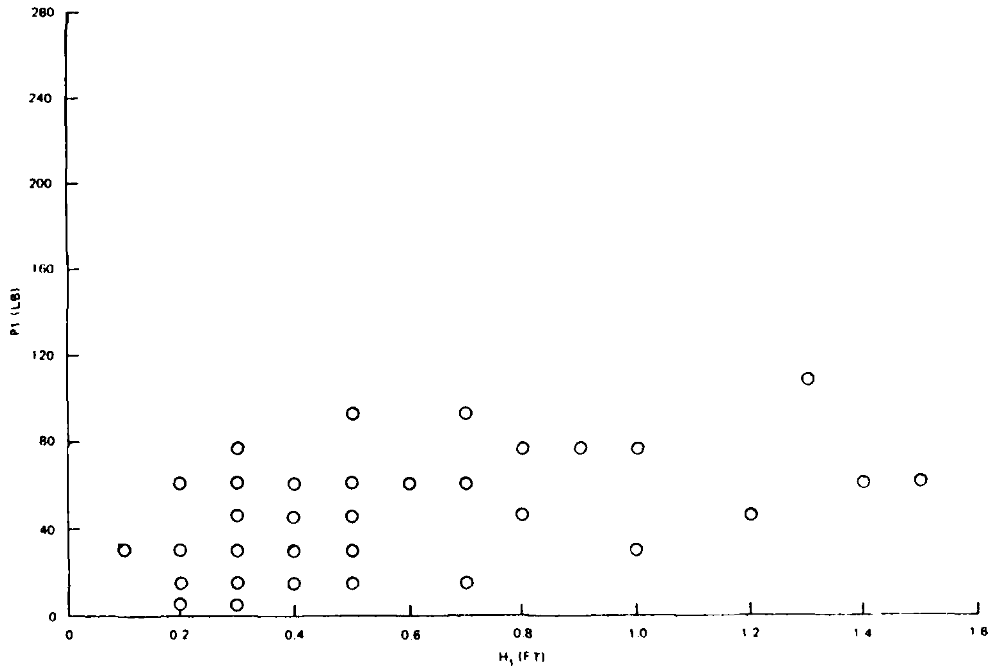

Figure 15. Anchor load at piling connection, P1, versus incident wave height, H_i

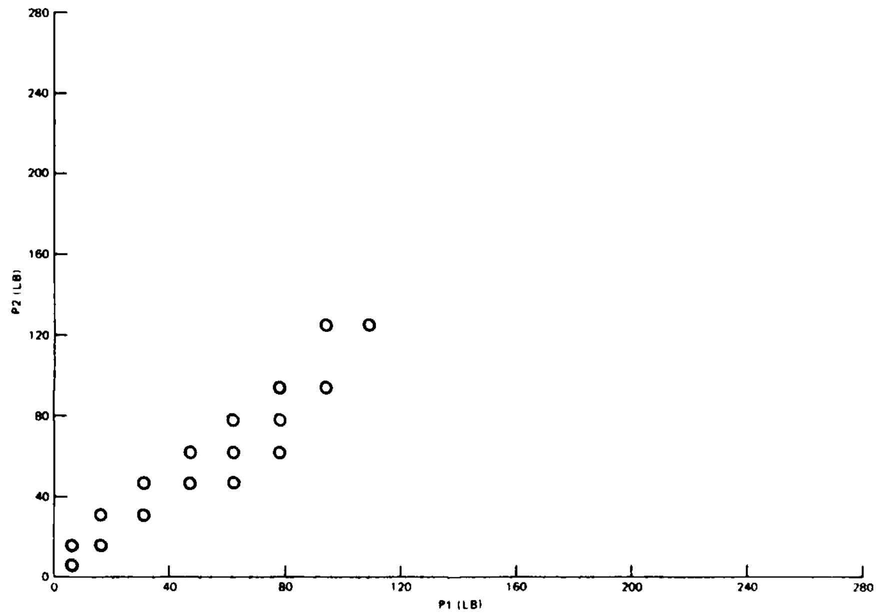

Figure 16. Anchor load at breakwater, P2, versus anchor load at piling, P1

PART VI: DISCUSSION

40. Numerous test runs involving various boat speeds, sailing lines, and angles of approach revealed that the wake generating vessel produced a maximum wake height of 1.6 ft at full throttle (26 knots) while passing within 75 ft of the breakwater. This resulted in a peak mooring line load of 281 lb. Specifications describing the type of polyester rope used for the mooring lines list the breaking strength at 19,400 lb. The working load is 2,134 lb (11 percent of the breaking strength); therefore, forces of similar magnitude to the boat wake induced forces recorded in this study should have no effect on the integrity of the mooring system.

41. Although the measured forces were quite low, they compare well to data from similar studies. The relatively low mooring loads recorded during the Floating Breakwater Prototype Test Program have been mentioned earlier. A similar prototype study was performed by the Canadian National Water Research Institute at a small marina in Burlington, Ontario, during 1981 and 1982 (Bishop 1984). The breakwater tested there was also a Goodyear design; however, moorings consisted of steel chains connected to concrete gravity anchors. Therefore, they lacked the elastic properties of the Pickering Beach and Puget Sound mooring systems. In addition to the electronic instrumentation utilized at Burlington, a mechanical load gage was installed on each of four windward anchor chains to measure the largest loads. The gages were in place for approximately five months, and the largest loads encountered were 1,214 lb on a center line and 1,417 lb on a corner line. These loads were induced by storm generated waves with heights estimated at 2.1 ft or less.

42. These particular studies indicate that stresses on an FTB mooring system caused solely by typical storm generated waves in short fetch areas or by boat wakes do not approach magnitudes which correspond to conditions which may cause failure of a mooring line or a related connection. However, mooring line failures did occur at Pickering Beach in the early stages of the SECDP study, and on the first site visit of the tests documented here, the corner anchor line to be instrumented was found broken. It was stated earlier that evidence suggested the anchor block displacements which occurred in 1978 were due to a severe combination of forces resulting from ice accumulation and winter storm generated waves. Inspection of the entire mooring system during the 1985 tests suggested that breakage of the severed corner line may have

been initiated by abrasion of the polyester rope near the connections at the anchor pile and at the breakwater. One line was found looped around its corresponding anchor pile and evidence of substantial wear at that point was obvious (Figure 17). The location of the breakage in the northeast corner line indicated that a similar situation may have caused its failure. It is possible that typical forces in the lines caused by storm generated waves coupled with mooring lines weakened at points of abrasion could cause failures in the mooring system at the Pickering Beach FTB.

Figure 17. Photo depicting mooring line looped around anchor pile. Note unnecessary hardware and possible abrasive surfaces

43. Measures to detect and prevent such failures in the future could be relatively inexpensive. Clump weights near the anchor pile connections could help alleviate the looping of excess slack around the pilings; however, a simpler and less expensive alternative would be to remove all unnecessary hardware from the piles. Required shackles, eyebolts, etc., without sharp

or abrasive edges could be used where connections are made. A periodic inspection of the breakwater could help detect these and other types of problems before they cause or contribute to breakwater failures. Inspection of the Pickering Beach breakwater would be relatively simple and inexpensive since, at low tide, the structure is essentially resting on the bay floor exposing features of the FTB which ordinarily would require inspection by divers.

44. One of the primary objectives for installing an FTB at Pickering Beach was to evaluate its ability to protect the nourished beach behind it. Throughout the history of the SECDP, it has been demonstrated that an FTB can, in some cases, serve as an effective structure to be included in beach stabilization efforts. The breakwater at Pickering Beach functioned mainly as a sediment trap and the fine grained (silt and clay) bottom sediments typical of the project site have accumulated substantially in the area behind the structure. In addition, the beach in the shadow of the breakwater is slightly wider than the remainder of Pickering Beach that was renourished in 1978. The presence of the FTB may have contributed to this slight expansion.

45. A related problem exists with the breakwater's tendency to collect sediment in the tire wells. The fact that the structure rests on the bay bottom at low tide contributes significantly to this problem. Holes were drilled at the lowest points in the tire wells to allow sediment to escape; however, the tires throughout the breakwater tend to rotate around the conveyor belting as the structure moves in response to waves. As a result, many of the holes drilled are no longer in the correct position to allow sediment escape. Several modules on the southeastern corner of the breakwater are presently submerged at higher tides due to this problem.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

46. Based on the test results reported herein, it is concluded that:

a. In conjunction with data collected at Puget Sound (Nelson and Broderick 1986), it is apparent that boat wake induced loadings, whether in deep or shallow water, do not exert significant stresses on a floating breakwater to threaten its mooring system or other features of its structural design.

b. The tests documented herein resulted in a successful evaluation of boat wake induced loadings and related stresses on a structure of this type. Specific knowledge gained from this effort includes:

(1) Efforts should be made to anticipate any possible alterations in the original test plan caused by meteorological conditions (such as the winds in this particular study).

(2) Results of this monitoring effort suggest that visual observations and recordings of transmitted wave heights were not accurate enough for comparison with electronically recorded incident wave data. A second electronic wave staff located behind the breakwater would have increased the reliability of the transmitted wave data.

c. The test results and field experience at this site have the following implications for the design of FTB's:

(1) Ice conditions can be the most severe factor causing damage to FTB's. Although the ice conditions in the winter of 1978 were not unusually severe, the forces induced by the ice cover coupled with storm generated wave forces were of sufficient magnitude to cause substantial structural damage to the Wave-Maze breakwater and cause displacement of 4-ton anchor blocks for both the Goodyear and the Wave-Maze breakwaters.

(2) Comparison of loads measured at each end of a mooring line indicate that forces near the connection to the breakwater may be as much as 25 percent higher than the corresponding forces measured near the connection to the anchor pile.

(3) When chains are used as all or a portion of the mooring lines, fatigue due to abrasion of adjacent links may be more significant than high magnitude point loadings in response to wave activity.

(4) The 3/4-in.-diam polyester rope mooring lines have performed adequately thus far. The strength, durability, and elasticity of synthetic ropes make them a good alternative when choosing a mooring line material. Designers should consider minimizing the potential number of abrasive surfaces near the mooring line connections.

(5) At the Pickering Beach site, individual tires were very susceptible to siltation which decreased their buoyancy. Holes placed in the tire bottoms did not alleviate the

problem due to tire rotation. One-half pound of foam was placed in the crown of each tire during construction of the Pickering Beach FTB. Designers should consider increasing the amount of foam, especially when the breakwater will be located in shallow depths or areas prone to siltation.

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Table 1

Experimental Results

Date	Run No.	Vessel Speed knots	Sailing Line To FTB ft	Wave Angle deg	Wake Height 1 ft	Wake Height 2 ft	Wake Height 3 ft	Transmitted Wake Height ft	Transmitted Coefficient Ct	Wave Period 1 sec	Wave Period 2 sec	Wave Period 3 sec	Anchor Load 1 (pile) lb	Anchor Load 2 (BW) lb
08-28-85	1	15	75	45	0.5	1.0	0.2			4.2	3.0	8.4		125
08-28-85	2	15	75		0.4	0.9	0.3			4.2	2.4	9.0		62
08-28-85	3	20	75		0.4	1.2	0.3			3.6	3.0	8.4		172
08-28-85	4	20	75		0.4	1.1	0.2			4.2	3.6	10.2		125
08-28-85	5	26	75		0.2	1.5	0.3			3.6	2.4	7.8		94
08-28-85	6	26	75		0.2	1.5	0.3			3.0	2.4	7.2		188
08-28-85	7	15	150		0.1	0.3	0.2			6.0	4.2	13.2		47
08-28-85	8	15	150											
08-28-85	9	20	150		0.2	0.5	0.2			4.8	3.6	11.4		94
08-28-85	10	20	150											
08-28-85	11	26	150		0.2	0.5	0.2			4.8	3.6	11.4		156
08-28-85	12	26	150											
08-28-85	13	15	200		0.1	0.4	0.1			4.8	3.6	10.8		141
08-28-85	14	15	200											125
08-28-85	15	20	200											
08-28-85	16	20	200											
08-28-85	17	26	200											156
08-28-85	18	26	200											141
08-28-85	19	15	250											78
08-28-85	20	15	250		0.1	0.5	0.2			7.2	3.6	14.4		109
08-28-85	21	20	250		0.1	0.5	0.3			4.2	3.6	10.2		125
08-28-85	22	20	250											
08-28-85	23	26	250											
08-28-85	24	26	250											
08-28-85	25	15	250		0.4	1.0	0.7			7.8	4.8	15.6		94
08-28-85	26	15	250		0.2	0.7	0.6			4.8	4.2	12.0		47
08-28-85	27	20	250		0.2	0.7	0.7			7.2	4.8	14.4		109
08-28-85	28	20	250		0.5	0.6	0.6			6.6	4.8	13.8		125
08-28-85	29	26	250		0.2	0.7	0.7			5.4	3.6	12.0		109
08-28-85	30	26	250		0.1	0.8	0.6			4.8	4.2	11.4		109
08-28-85	31	20	75	90	0.3	0.7	0.5			4.8	3.6	10.8		125
08-28-85	32	26	75		0.3	0.8	0.9			4.8	3.6	10.2		172
08-28-85	33	20	75		0.6	1.3	1.0			3.6	2.4	7.8		203
08-28-85	34	26	75		0.6	1.6	0.3			3.6	2.4	7.2		281
08-28-85	35	20	100		0.5	0.8	1.0			3.6	3.0	9.0		125
08-28-85	36	26	100		0.3	0.8	0.5			4.2	3.0	9.0		94
08-28-85	37	20	200		0.3	0.7	0.7			4.8	4.2	10.8		125
08-28-85	38	26	250		0.3	0.7	0.5			4.2	4.2	10.2		94
08-29-85	1	15	75	45	0.4	1.0	0.3	0.8	0.80	4.2	3.0	9.0	31	31
08-29-85	2	15	75		0.5	1.0	0.4	0.7	0.70	3.6	3.0	8.4	31	31
08-29-85	3	20	75		0.5	0.7	0.7	0.7		3.0	2.4	7.2	16	31
08-29-85	4	20	75		0.4	1.4	0.1	0.4	0.29	3.0	2.4	6.6	62	62
08-29-85	5	26	75		0.3	0.9	0.5	0.5	0.56	3.0	2.4	7.8	78	94
08-29-85	6	26	75		0.3	1.5	0.1	0.4	0.27	3.0	2.4	7.2	62	47
08-29-85	7	15	150		0.2	0.5	0.3			7.2	3.6	14.4	16	16
08-29-85	8	15	150		0.2	0.5	0.3	0.5		6.6	3.6	12.6	31	31
08-29-85	9	20	150		0.2	0.4	0.3			4.8	4.2	11.4	16	16
08-29-85	10	20	150		0.2	0.4	0.4			5.4	3.6	11.4	47	47
08-29-85	11	26	150		0.1	0.3	0.3			4.2	3.6	10.2	31	31
08-29-85	12	26	150		0.1	0.3	0.2			4.8	3.6	10.8	62	62
08-29-85	13	15	200		0.2	0.3	0.1			7.2	4.2	13.8	47	47
08-29-85	14	15	200		0.3	0.3	0.2			6.0	3.6	[illegible]	31	31
08-29-85	15	20	200		0.2	0.3	0.3			6.6	3.6	13.8	31	31
08-29-85	16	20	200		0.2	0.3	0.2			4.8	3.6	11.4	78	78
08-29-85	17	26	200		0.2	0.2	0.2			8.4	3.6	[illegible]	62	62
08-29-85	18	26	200		0.1	0.2	0.2			2.4	6.6	11.4	16	16
08-29-85	19	15	250		0.2	0.5	0.5			11.4	4.8	[illegible]	62	78
08-29-85	20	15	250		0.2	0.2	0.2			7.8	4.2	[illegible]	6	6
08-29-85	21	20	250		0.2	0.2	0.1			6.6	4.8	13.8	16	16
08-29-85	22	20	250		0.1	0.1	0.2			7.8	4.2	15.6	31	47
08-29-85	23	26	250		0.1	0.2	0.2			6.6	4.8	14.4	31	47
08-29-85	24	26	250		0.1	0.2	0.2			6.0	3.6	13.2	6	16
08-29-85	25	15	75	90	0.5	0.5	0.3			6.6	3.0	11.4	94	125
08-29-85	26	15	75		0.4	0.5	0.3			4.8	3.0	9.6	16	31
08-29-85	27	20	75		0.4	0.6	0.2	0.4	0.67	6.0	3.0	10.8	62	62
08-29-85	28	20	75		0.4	0.7	0.3	0.4	0.57	4.2	2.4	8.4	94	94
08-29-85	29	26	75		0.5	1.2	0.2	0.4	0.33	4.2	2.4	8.4	47	62
08-29-85	30	26	75		0.7	0.8	0.3	0.6	0.75	4.2	2.4	8.4	47	62
08-29-85	31	15	150		0.4	0.2	0.1			6.6	3.0	13.2	16	16
08-29-85	32	15	150		0.3	0.8	0.3	0.5	0.63	4.8	3.6	11.4	78	94
08-29-85	33	20	150		0.4	0.7	0.4	0.4	0.57	6.6	3.0	12.0	62	62
08-29-85	34	20	150		0.2	0.4	0.2	0.4		5.4	3.0	10.8	31	47
08-29-85	35	26	150		0.3	0.3	0.3	0.3		3.6	3.6	9.6	31	31
08-29-85	36	26	150		0.1	0.4	0.3	0.4		4.2	3.6	10.2	31	31
08-29-85	37	15	200		0.4	1.0	0.6	0.7	0.70	11.4	4.8	19.8	78	78
08-29-85	38	15	200		0.2	0.2	0.2			6.0	4.8	12.6	16	16
08-29-85	39	20	200		0.3	0.4	0.2			6.6	4.2	13.8	62	78
08-29-85	40	20	200		0.3	0.5	0.1	0.4	0.80	5.4	4.2	12.6	31	47
08-29-85	41	26	200		0.1	0.3	0.1			6.0	4.2	12.0	16	16
08-29-85	42	26	200		0.3	0.3	0.2			5.4	4.2	[illegible]	16	16
08-29-85	43	15	250		0.5	0.5	0.2	0.3	0.60	9.6	5.4	18.0	47	47
08-29-85	44	15	250		0.3	0.3	0.1			8.4	7.8	20.4	47	62
08-29-85	45	20	250		0.2	0.3	0.2			6.0	3.6	13.2	78	62
08-29-85	46	20	250		0.3	0.4	0.1			7.2	4.2	14.4	16	31
08-29-85	47	26	250		0.2	0.3	0.1			6.0	3.6	12.6	6	6
08-29-85	48	26	250		0.1	0.3	0.2			3.0	2.4	7.2	16	16
08-29-85	49	15	200		0.5	1.3	0.5	0.8	0.62	9.0	4.9	16.8	109	125

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